Optimization of the surface crack on the human lumbar vertebra

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Abstract: The goal of this study is to optimize the surface crack parameter of the lumbar spine using probabilistic and finite-element analysis. The model was constructed based on the actual size of vertebra. In order to simplified the model, vertebra was assumed as an isotropic, linear and symmetrical model with all components meshed by tetrahedral element whereas hexahedral for crack structure. Most of the vertebra fracture is caused by compressive loading due to the high-energy impact or lifting heavy goods. In addition, unilateral pedicle crack is close related to the compressive loading on the posterior region. However, this biological structure involved too many uncertainties in terms of mechanical properties, loading and geometry. Therefore, probabilistic analysis was performed to cater the problem that unsolved by deterministic analysis. Probabilistic and optimization techniques were used to measure the correlation between input parameters of the bone failure based on the yield stress and fracture toughness consideration. Furthermore, the sensitivity analysis will emphasize and validate the crucial parameters that should be stress and focus on the failure criteria.
Keywords: Optimization, Monte Carlo, Crack, Lumbar, Spine.

1. Introduction

Low back pain (LBP) is one of the most common medical problems that interferes the community work and leisure time activities [1-5]. There is chances of a person having LBP during the lifetime is increases with age due to the decreases of bone mass density (BMD) [6]. Therefore, the elderly patient normally associated with osteoporosis has surface crack to induced the bone fracture [7, 8]. The special characteristics of the life biological structure is it can to repair any deteriorated mass or flaws. Crack is one of the flaw occurred on the vertebra to produce fracture. However, if the repair rate of crack is higher than the fracture rate, the failure will not happen.

Basically, the fracture of the posterior regions are relatively uncommon chance to the patient especially in low energy falls. To support that statement, Yingling et al. [9] was reported that the failure at low load rates occurred on the endplate, whereas the higher load rates appeared more on vertebral body. The pedicle fracture on the lumbar vertebrae is called pediculolysis and it is most commonly unilateral [7]. This is mean that the fracture only applied on each side of pedicle. The symptoms of back pain are related with vertebral compression fractures (VCF), that may be caused by sudden high energy impacts such as falls and accidents [10]. High energy impacts represents the high velocity rate of the loading conditions over a short time period. This conditions will induce the spinal fractures by small size of displacement [11].

Traditionally, deterministic analysis employed a fixed values for the parameters that control the behavior of the structure. Three main categories in defining the variables are geometry, loading and material properties. Carolina et al. [12] used only four random variables which is joint load, angle applied, and material properties for bone and the implant design analysis. In this study, lumbar vertebra plays a lot of uncertainties that affected to the bone failure. The analysis will be more significant and degree of uncertainty also increased if more parameters are considered into account. The computational modeling approaches are considered suitable for these type of problems due to the time and resources constraint. In addition, the parameters extremely produce large combination between the input variables. Due to these, different loads and boundary conditions the results of current studies are usually incomparable and may take on unrealistic values [13].

In order to validating the results from probabilistic analysis, optimization approach was suggested to be an advanced predicted parameters that produce the bone failure. It can computes parameter more efficiently and at the same time constraining the material properties of the different spinal structures [14]. Predicting model of the lumbar spine was capable to cater the problem by different loading conditions, material properties and geometry of the crack.

The aim of this study is to determine the crucial input parameters that affected to the bone failure response. Finite element analysis was performed as data collection for probabilistic and optimization methods acquire the statistical analysis measurement. The hypothesis for this study is mode I become the most crucial factor to the surface crack fracture.

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2. Methodology

2.1 *Modeling of Lumbar Vertebra*

A 3D sagittal symmetric rigid body model of the human lumbar spine was developed using SolidWorks software and measure the stress and strain analysis by Ansys software. For many mobility injuries L2-L3 lumbar spine component is responsible to the bone fracture. Thus, L2 vertebra has choose to be as part of the analysis in this study. A model validation in Fig. 2(a) was compared with previous model by Shirazi-Adl [15] Fig. 1(b) and it is considered the geometry well similar. Then, the material properties were summarized in Table 1.

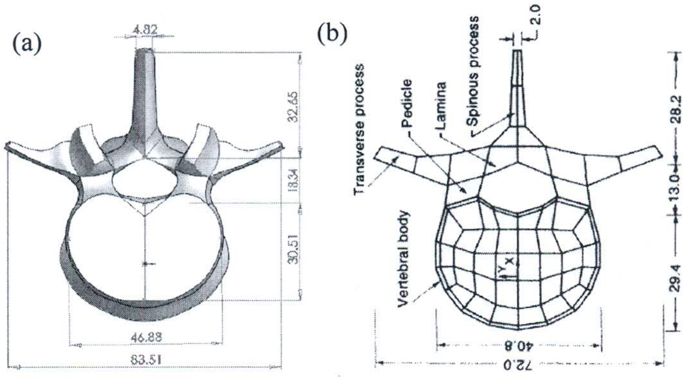

Fig. 1 Vertebra lumbar geometry (a) current (b) Shirazi-Adl [15]

Table 1: The material properties of modeling

Parameters	Description	Mean	COV[a]	Distribution
YOUNG	Young Modulus	12 GPa	0.21	Lognormal
POISSON	Poisson ratio	0.3	0.017	Lognormal
FORBDY	Body force	414 N	0.1	Normal
FORFCT	Facet force	46 N	0.1	Normal
AREBDY	Body area	1298 mm^2	0.1	Lognormal
AREFCT	Facet area	166 mm^2	0.1	Lognormal
WR	Weight ratio	0.59	0.01	Uniform
W	Body weight	80 kg	0.1	Normal
R	Crack size	3.0 mm	0.04	Normal

[a]coefficient of variation

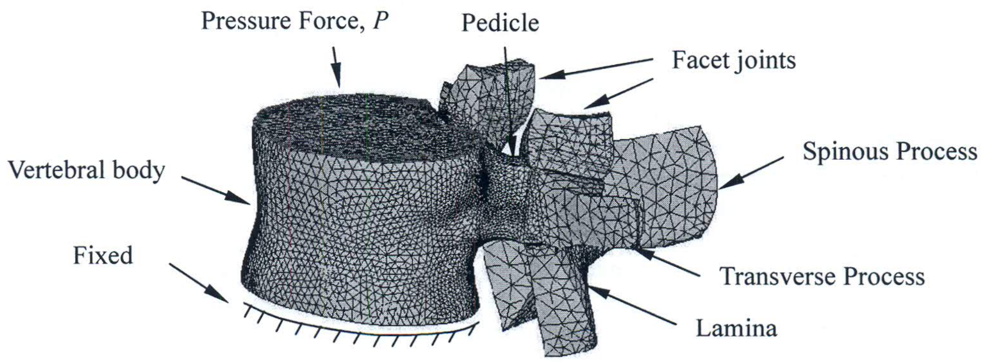

Fig. 2: Vertebral anatomy and boundary condition

Anatomy of the vertebra was shown in Fig. 2. Generally, it separated into two region which is anterior and posterior region. Posterior region comprises with the several components, pedicles, facet joints, spinous process, transverse process and lamina. The main function of this region is to protect the spinal cord from any injury or external forces directly. Hence, any crack or failure to that region will affect the spinal cord as well as the whole body system.

2.2 *Fracture Toughness*

For simple boundary value problems with idealized crack geometry, the stress intensity factor (SIF) or fracture toughness may be expressed as

$$K = f \cdot \sigma\sqrt{\pi R} \tag{1}$$

where f is correction factor, σ is applied stress and R is crack radius. Alternatively, fracture toughness can be derived in terms of the strain energy release rate, G, defined as the change in potential energy per unit increase in crack area. For linear elastic release rate (LEFM), the relationship between strain energy and SIF were close. It can be expressed in terms of the mode I, II, and III as follows:

$$G = \frac{K_I^{\,2}}{E'} + \frac{K_{II}^{\,2}}{E'} + \frac{K_{III}^{\,2}}{2\mu} \tag{2}$$

where μ is the shear modulus, υ is Poisson ratio and E' is defined as follows:

$$\begin{aligned} E' &= E(\text{Young Modulus}) \text{ in plane stress} \\ E' &= E/(1-\upsilon^2) \text{ in plane strain} \end{aligned} \tag{3}$$

There are three type of modes of crack loading condition as shown in Fig. 3. Mode I represent the crack opening, Mode II is cracked sliding, and mode III is tearing. Traditionally, SIF is given by the subscript such as K_I, K_{II}, or K_{III}. This model is involved the biomechanical structure condition, thus one mode of loading condition is not represent the real picture of analysis. Therefore, three modes of loading must be considered to ensure that the simulation is represents the real condition.

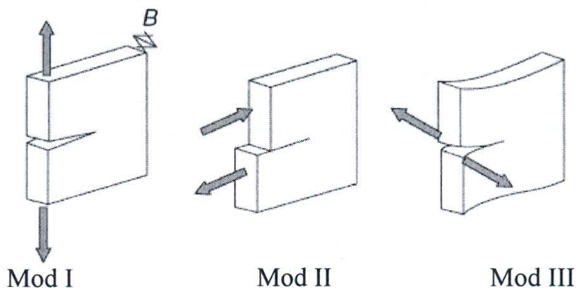

Fig. 3 Three types of crack modes [16]

2.3 *Element Sensitivity*

The element sensitivity for meshing is immerse important in ensuring a more accurate analysis result. The contours of maximum stress was appeared on the pedicle region. The refined mesh was focused only on that region instead of the whole model. However, the mesh density should not exceed the appropriate elements to allow analysis become faster. Fig. 4 indicates that the increasing of the element will affecting the stress distribution on the model.

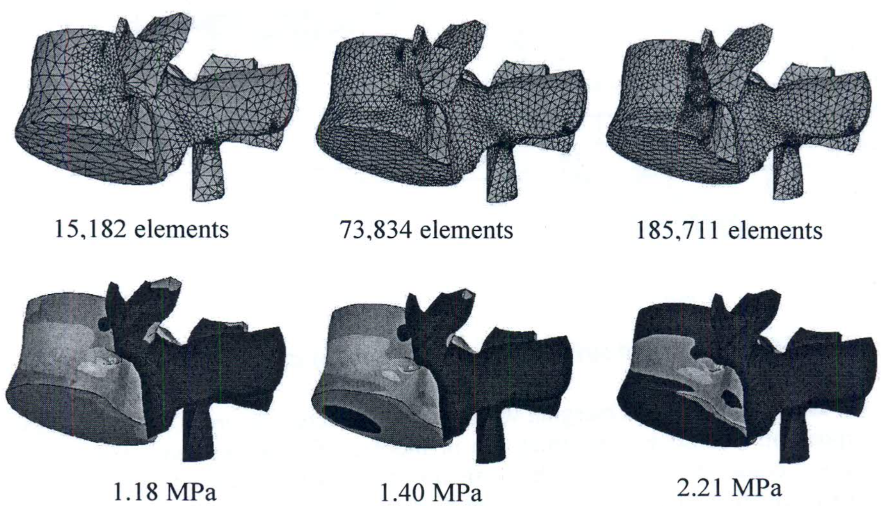

Fig. 4: Different mesh density on pedicle

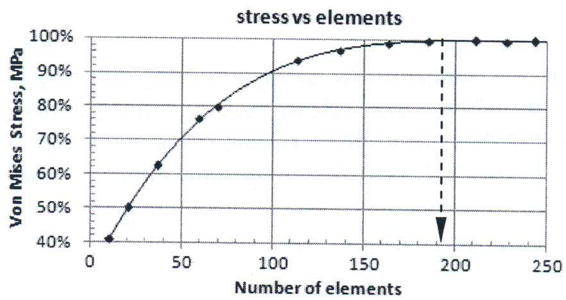

Figure 5: Element sensitivity analysis

Fig. 5 shows that the graph of stress versus the number of elements in percent (%). Stress refers to the proportion of stress distribution between the minimum and maximum values of the model. Stress with a value of 100% is represents the number of elements to achieve an optimum elements. Therefore, a number of optimum elements to meshing this vertebra exhibit by dashed line arrow which is 185,711 elements with stress 2.21 MPa. This appoint element was taken due to the graph depicted no changes occurred despite increase the number of elements. This phenomenon proves that the density of the mesh is in optimum condition. Therefore, the optimum number of elements acquired can be seen through graph in Fig. 5.

Based on evaluation for three nodes as shown in Fig. 6, the highest stress is for node *I* while node *II* is lower than node *III*. In contrast, SIF for node *I* is the lowest and node *III* much greater rather than others node. It is due to the loading and shaped condition that subjected to the model. From Fig. 6, the crack path distribution was creating on the crack structure development. Semi-ellipse form of crack structure was developed from pedicle region since to represent pediculolysis fracture happen on the vertebra.

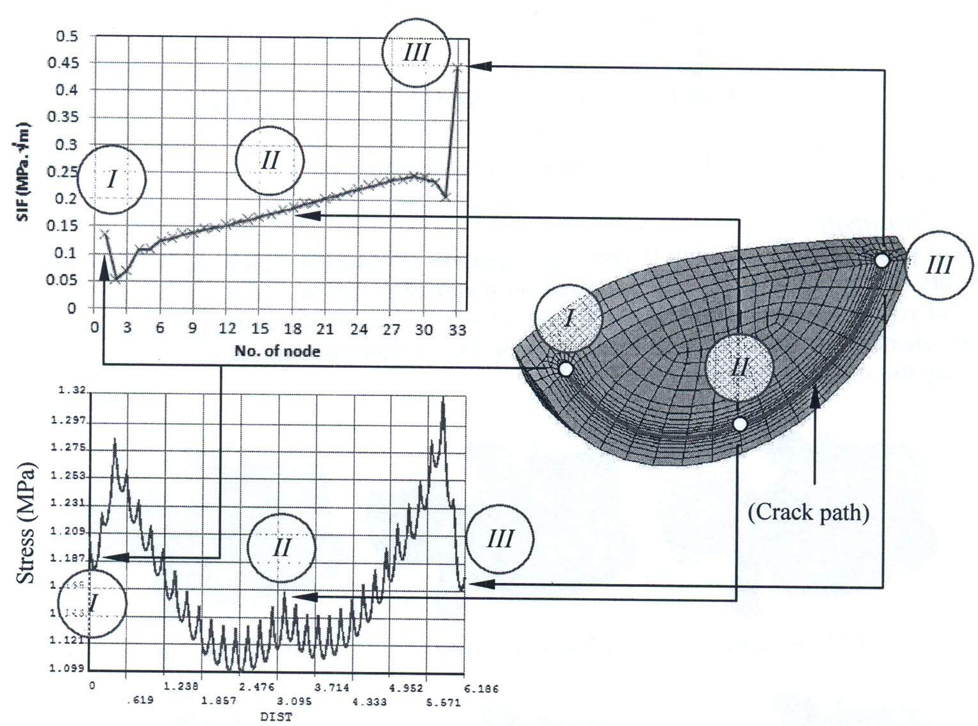

Fig. 6: Crack path distribution node based on (a) stress, and (b) SIF

Consequently, the crack structure was merging with the body structure in order to applied superposition technique. Superposition technique is splitting two or more configurations separately in simplify the model. In this case, crack structure and the vertebral body were modeled individually before it combined together to create a single volume. However, the crack structure and vertebra body are using type of mapped and free meshing respectively. To ensure that the synchronization between these two types of meshing, automatic meshes has been performed to attached the nodes and element together. The boundary between crack and body structure are certifying to have an appropriate meshing size to obtain accurate results. Full model is represented by associated both model as depicted in Fig. 7. However, the crack structure only considered for one side of pedicle to represent the unilateral pediculolysis fracture.

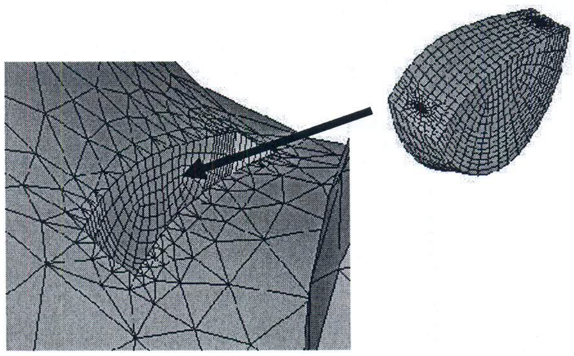

Fig. 7 Crack structure development incorporated with body pedicle

Superposition principle was employed to determine the SIF, in order to avoid crack structure of the model. This technique required to develop the crack structure before associated together with the vertebra. The important region is refined using finer meshes to enable the reliable results are necessarily produced mainly in the analysis.

3. Results and Discussion

There are 33 nodes applied along the crack path depends on the meshing size. To ensure that the nodes constant in the future, meshing size has been fixed. The stress distribution along the crack path can be seen through in Fig. 8. It indicates that the highest stress located at the crack tip for both ends in point *I* and *III* (refer Fig. 6). The pattern of the stress distribution are based on the crack structure shape and loading angle. On the other hand, both ends of crack path are on the pedicle surface and it easy to exposed by fracture. Therefore, the surface crack is the typical problem in the bone structure especially in the osteonal bone sections [17]. However, the microcrack within the osteonal bone can be arrested by the structure of the osteon which is consists of Haversian canal and lamellae.

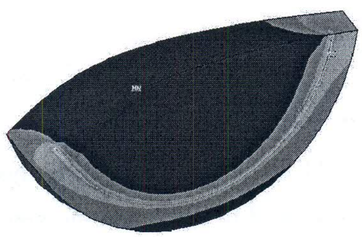

Fig. 8: Stress distribution along the crack path.

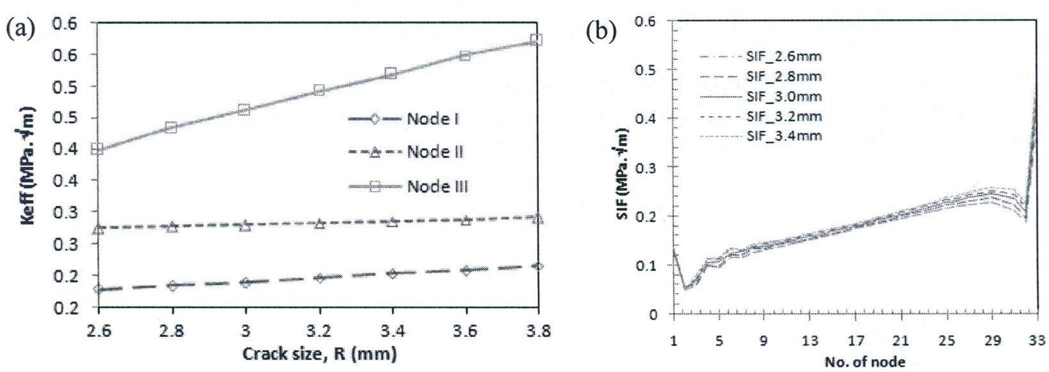

Fig. 9: Stress intensity factor for different crack sizes (a) three nodes, (b) all nodes along crack path

The SIF value of different nodes along the crack path is represent by Fig. 9. Three selected nodes depicted in Fig. 9 is (a) to analyze any changes of fracture of each node. Obviously, node *III* shows the highest gradient of slope also the SIF value. Increasing of these SIF values are represented as linear relationship for all selected nodes. However in Fig. 9(b), the SIF value is performed in more specific for all nodes related along the crack path. The trend of SIF is consistent in between four to thirty nodes number but the rest are not. It is due to the configuration of loading and crack shape influence the result. Furthermore, node *III* is the farthest point to the loading on the facet joint and it create the biggest moment compared to the others node along the crack path.

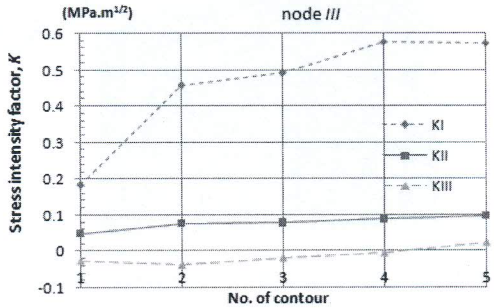

Fig. 10: Stress intensity factor for three modes of crack.

In order to determine which mode is represent the critical condition for this type of crack can be concluded in the Fig. 10. Five contours of the meshing was selected to be as reference around the crack tip in node *III*. Obviously, mode I or K_I become the most critical mode compared to the mode II and mode III. It is well agreed with our hypothesis earlier. Mode I also increase abruptly and it is very sensitive to the loading condition applied to that model.

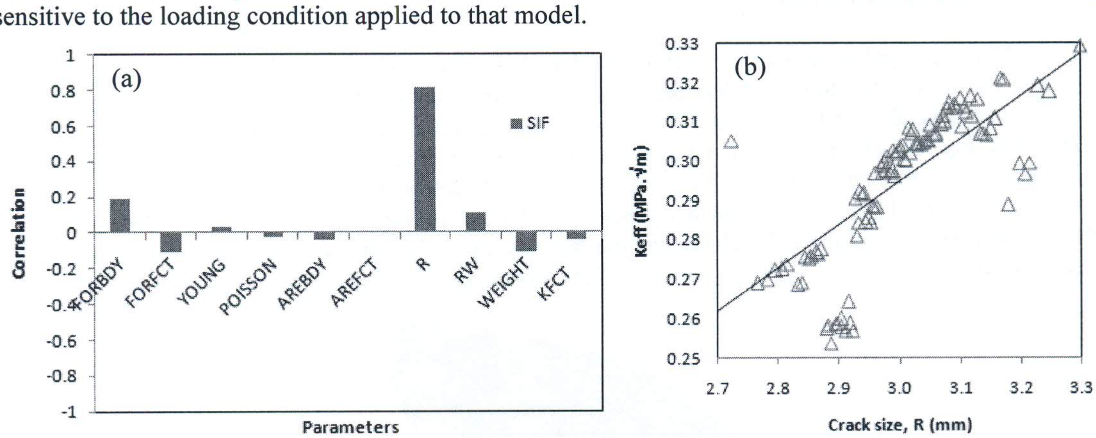

Figure 11 Sensitivity parameter analysis

Spearman correlation measurement was used to determine the sensitivity parameter with monotonic relationship. From Fig. 11 (a), the most sensitive parameter to the fracture toughness evaluation is crack size. Beside it, the parameter is almost equivalent to one which is 0.811. It denotes that only crack size sensitive and significant to the vertebra failure rather than others. Therefore, the crack parameter needs to be highlighted to control the vertebra failure conditions. Whilst, the Fig. 11 (b) illustrates the scatter plot of input-output parameters with 100 samples in order to correlate between them. The slope gradient of this graph indicates the Spearman rank order correlation coefficient for SIF (output) and crack size (input) to validate Fig. 11 (a).

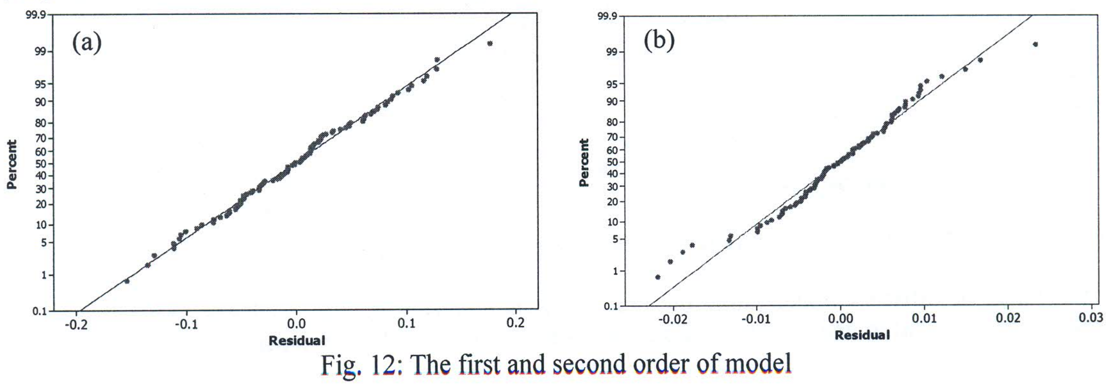

Fig. 12: The first and second order of model

Table 2: Probability of each parameter considered

Parameter	Probability
FORBDY	0.509
FORFCT	0.664
YOUNG	0.461
POISSON	0.048
AREBDY	0.196
AREFCT	0.579
R	0.001
WR	0.240
W	0.187

To optimize all the parameters considered in this analysis, Response Surface Method (RSM) was used as comparison with the probabilistic analysis. Table 2 illustrates that the probability of each parameter considered in this analysis. The sensitive parameter is represent by the probability lower than 0.05. The design of experiment using RSM shows that only crack size, *R* and poisson ratio, *POISSON* contribute significantly on the maximum stress since $P<0.05$. R-square displays that 97.2 percent data close to the normal distribution. Normal distribution plot shown in Fig. 12(a). The first order model equation is shown below :

$$Maxstress = -1.63 + 1.13 \times 10^{-4}\,(\mathrm{FORBDY}) + 1.32 \times 10^{-4}\,(\mathrm{FORFCT}) + 2.02 \times 10^{-12}\,(\mathrm{YOUNG}) - 2.79\,(\mathrm{POISSON}) - 6.95 \times 10^{-5}\,(\mathrm{AREBDY}) + 2.43 \times 10^{-4}\,(\mathrm{AREFCT}) + 3.24\,(\mathrm{R}) - 0.87\,(\mathrm{RW}) - 1.12 \times 10^{-3}\,(\mathrm{WEIGHT}) - 8.92 \times 10^{-4}\,(\mathrm{KFCT})$$

For the model equation above, the percent of error was counted as 0.7%. The error was determine by comparing the predicted value by equation and real value measured by finite element analysis.
The design of experiment using RSM second order shows that only *R* and *POISSON*WEIGHT* ratio contribute significantly on SIF since $P<0.05$. R-square shows that 84.2 percent data close to the normal distribution and percent of error is 0.62%. Normal distribution plot shown in Fig. 12(b). The second order model considered all the relationship between parameters, and it takes more time to analyze. Both analysis for maximum stress and SIF is indicates the same sensitive parameter which is crack size, *R*. Although the percent of error by SIF is higher than maximum stress, the data still close to the normal distribution. The highest error obtained from SIF is due to the many variables were includes in the analysis and it affect to the response.

4. Conclusion

Finite element analysis was performed to measure the SIF for vertebra structure in the unilateral crack. This study objective is achieved to determine the probability of failure of vertebrae under compressive loading and optimize the data. The uncertainties are reflected the structure to be fail depends on the three basic parameters in material properties, loading and geometry. All the uncertainties decided in this study are based on knowledge and experience. Effects of uncertainties in biological structure are significant into representing the real-life phenomena. The highest of stress intensity factor (SIF) was occurred on the node *III* which is the end of the crack path. In addition, mode I become the crucial type of crack mode particularly for this problem. Crack size, *R* becomes the most significant parameter affect the failure evaluation on sensitivity analysis and RSM. Therefore, emphasizing of this parameter is too crucial in order to avoid the system failure. This study is useful to investigate the inherent uncertainties and variations in biological structures.

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